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Optimization of Gravity-Driven Granular Flow Around the Tube for Heat Transfer Enhancement

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Nowadays, moving bed heat exchanger (MBHE) has been gradually adopted in the field of heat recovery from the granular flow. Compared with fluidized bed, the moving bed cost less. However, it usually brings with relatively poor heat transfer performance. The current study aims to optimize the heat transfer in gravity-driven granular flow through tube vibration, which is helpful to the efficient design of MBHE in the future. The vertical granular flow is numerically simulated with discrete element method, where careful discussion about vibration tube effect is developed. The model has been carefully validated. To focus on the mechanism of heat transfer enhancement, the geometry model is simplified as a single tube. The results show that, tube vibration in different directions could improve heat transfer performance, where the effect of horizontal vibrating direction is more remarkable. It’s also found that a slight sinusoidal vibration is able to accelerate particles update above the tube and drive some particles contact the bottom zone of tube. Therefore, it mitigates the negative effect of stagnation zone and void zone in cases of static tube. Then the heat transfer coefficients would increase. What’s more, tube vibration would rebound particles around the wall, where additional mass diffusion is beneficial to heat transfer at sides of tube at some extent. However, it should be noted that vibration would increase wear rate between tube and particles significantly at the same time. The industrial application relies on the development of wear-resistant technology.

1. Introduction

Waste management is beneficial to sustainable development with less environmental problems (Li et al., 2018). Especially, there are huge waste heat sources containing in much industrial solid granular. Proper recycle for high temperature slag could reduce energy consumption and CO_2 emissions. Less CO_2 emissions have a vital role in low carbon sustainable energy transition (Dhar et al., 2018). Therefore, waste granular heat recovery has attracted many researchers’ attention. Qin and Chang (2017) designed four different life cycles for 1323 K coke oven coke, which strived for higher energy efficiency, exergy efficiency and less CO_2 emissions. Zheng et al. (2019) illustrated the heat transfer mechanism in a vertical tank for 1173 K sinter, and have derived several correlations about exergy heat transfer. Zheng et al. (2018) have recovered heat efficiently from 1073 K calcined petroleum coke by means of a moving bed heat exchanger. Due to lower cost and energy consumption, moving bed heat exchanger (MBHE) has been gradually adopted in the occasion. The indirect heat transfer realizes clean recovery, which would have a good application potential. However, compared with fluidized bed used frequently before, better performance of MBHE is strived.

To realize a wider range of application, many researchers have been studying the proper way to enhance the heat transfer in MBHE. Liu et al. (2015) analysed the effect of particles diameter, flow rate and arrangement of tubes on heat transfer. Nguyen et al. (2014) compared heat transfer performance between fin and no-fin tube, which proved that fin has the possibility to enhance heat transfer. Morris et al. (2016) designed arrays of hexagonal tubes instead of circular tubes in their equipment. These related studies belong to passive enhancement technologies more, and active enhancement technologies are required. Ansary et al. (2012) tried to improve performance of MBHE through tube vibration. But the preliminary experiment results were not satisfactory. There remain many issues worthy of explaining. In this study, the effect of tube vibration on heat transfer performance is carefully researched through discrete element method (DEM) by EDEM 2.6. For sake

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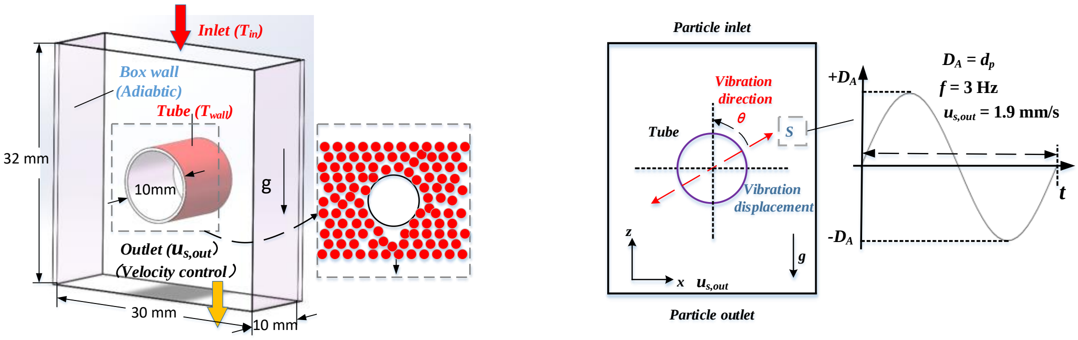
of saving computation cost, dense granular flow is simulated around a single tube. The conclusion could provide helpful prediction for optimized design of MBHE system.

2. Simulation

2.1 Methodology and simulation cases

Dense solid granular usually move slowly enough with outlet control in MBHE. The velocity magnitude is only mm/s (Liu et al., 2015), which has even decreased to 10-5 m/s (Zheng et al., 2018). Particles interaction dominants the motion, and interstitial gas makes little contribution. Besides, the effect of convection is limited (Hou et al., 2016). Therefore, solid phase is more focused on in current work, and gas phase is neglected. Discrete element method is applied here. Conduction and radiation have been both considered. The detailed description could be found in our previous work (Guo et al., 2018). The geometry and boundary conditions in the simulation are presented in Figure 1a. Firstly, random dense packing was generated. To study the effect of tube vibration on heat transfer, cases of static tube and vibrating tube were both simulated. Continuous sinusoidal vibrations in different directions were applied to the tube when the granular flow began, as shown in Figure 1b. The motion of a short steel tube was regarded as a rigid motion.



(a) Geometry and boundary conditions *(b) Vibration control*

Figure 1: Schematic diagram of simulation cases

The overall simulation process lasted 31 s. The process in the last 11 seconds was mainly analysed, when quasi-steady granular flow has occurred. To evaluate the heat transfer performance, heat transfer coefficients were calculated as Eq. (1). The q is average heat flux, and A is tube area corresponding to q.

$$h = q / \left(A \left(T_{in} - T_{wall} \right) \right) \tag{1}$$

Main parameters in the simulation are summarized in Table 1. The properties of particles refer to Liu et al.(2015), which is independent of temperature. As for the heat conductivity of gas， T_{wall} is the reference temperature. The operation could be validated in the next part.

Table 1: Main parameters for simulation

Parameter	ρ /(kg/m^3)	C_p /(J/(kg·K))	k_s /(W/(m·K))	k_f /(W/(m·K))	d_p /mm	T_{in} /K	T_{wall} /K	Δt /s
Value	2848	1210	0.55	0.0257	1.72	973	287	2.6×10^{-6}

2.2 Validation

To validate the DEM model, granular flow simulation would be compared with experimental data (Liu et al., 2015). Because the computation cost for cases in actual size is too expensive to support, a compromise proposal is adopted here. Firstly, heat transfer coefficients for a single tube ($h_{s,tube}$) are gained by the DEM model. The data would be used in heat calculation for actual MBHE afterwards. Based on the method described by Zhang et al. (2018), temperature of granular flow and water in the outlet is solved separately from different geometries and boundary conditions. The overall transformation process is illustrated in Figure 2. Finally, heat transfer coefficients for the tube bank ($h_{s,tube\text{-}bank}$) could be calculated as Eq. (2) for the validation.

The results are presented in Figure 3. The average relative error between $h_{s,tube\text{-}bank}$ and experimental data is 4.80%, and the max error is 9.74%. It indicates that DEM simulation is credible.

$$h_{s,tube-bank} = \frac{q_{v,s}\left(\rho c_p\right)_s\left(T_{s,in}-T_{s,out}\right)/A}{\left(T_{s,in}-T_{f,out}\right)-\left(T_{s,out}-T_{f,in}\right)}\ln\frac{\left(T_{s,in}-T_{f,out}\right)}{\left(T_{s,out}-T_{f,in}\right)} \tag{2}$$

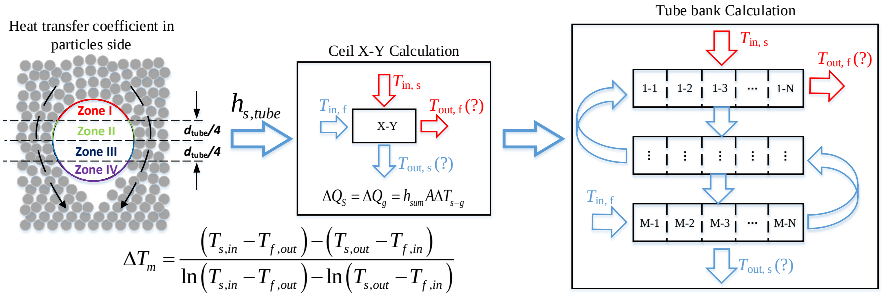


Figure 2: Heat transfer coefficient transformation (single tube to tube bank)

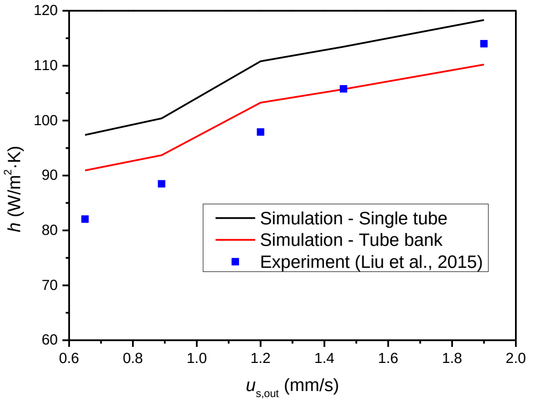
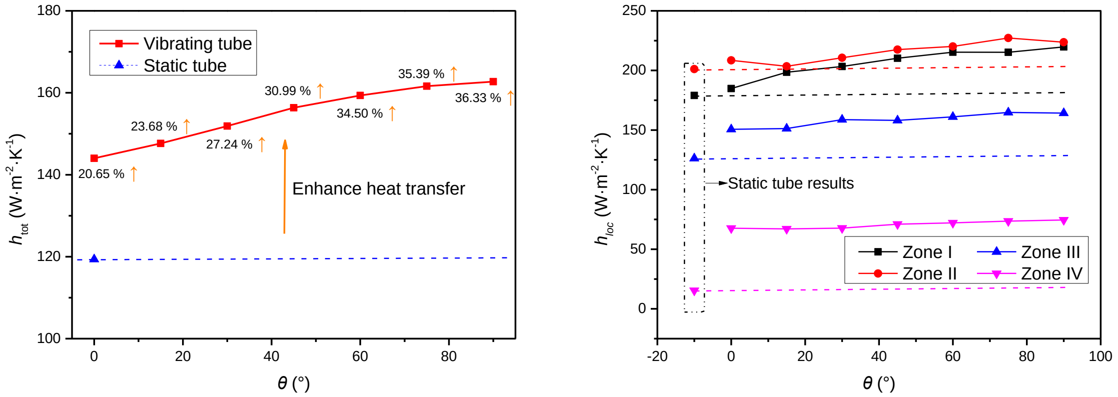


Figure 3: Validation of DEM simulation couple with heat transfer in granular flow

3. Results and discussion

The heat transfer performances are compared in Figure 4, where the descending rate is 1.9 mm/s. It's observed that the h_{tot} is improved through a slight vibration in any directions, which means the vibration could enhance heat transfer. But vibrations in different directions have different effects on heat transfer. It's found that the vibration closer to x-direction has more advantages on heat transfer. When the z-direction vibration turns into x-direction vibration, the overall heat transfer coefficient would increase by 20.65 % to 35.39 %.

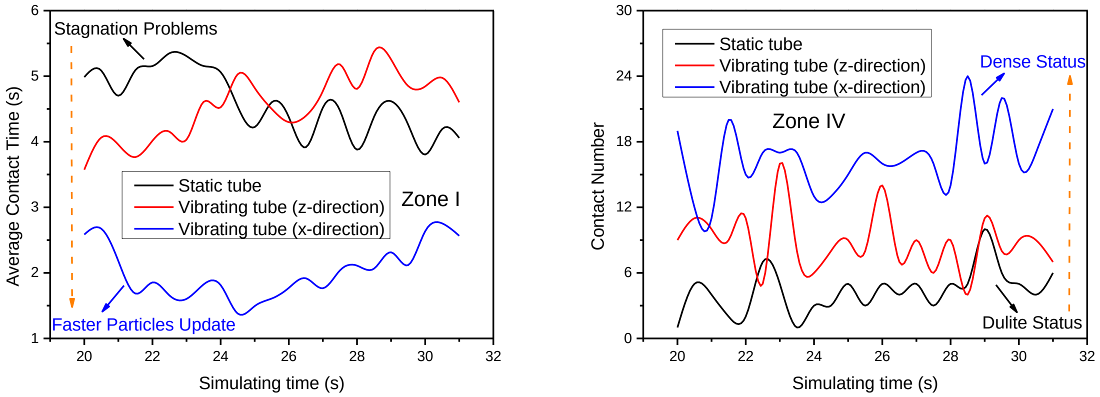
More information could be found in Figure 4b. As shown in Figure 2, the tube is divided into four zones equally in height to analyze the h_{loc}. For the case of static tube, there is a stagnation zone around Zone I, and a void zone around Zone IV. They limit the h_{loc}. As a whole, the major improvement occurs in Zone III & IV. The remarkable enhancement decides the positive effect of vibrations on heat transfer. However, the vibration closer to x-direction could improve the h_{loc} more in Zone I & II. It leads to the difference in Figure 4a. In fact, any vibrations consists of the x-direction and z-direction components. To demonstrate effects of vibrating directions more clearly, the contact between particles and tube is discussed in Figure 5 and Figure 6. Contact time is for particles. It records the total time for particles contacting the surface and reflects particles update. Figure 5a presents the contact time aound Zone I. It shows that, x-direction vibration decreases the time rapidly, while z-direction vibration plays little role. Hence, particles update is accelerated above tube successfully by x-direction vibration, and the h_{loc} is increased in Zone I. As for z-direction vibration, there still exist stagnation. Finally, the h_{loc} in Zone I is limited. Meanwhile, contact number is the amount of particles which contact the target zone. It explains the flow status of dense or dilute. The Figure 5b illustrates that, each vibration makes more particles contact the tube. Due to the vibration, more particles could contact the tube in Zone IV with heat transfer. Denser contact reduces the void around Zone IV, and the h_{loc} would increase.



(a) Overall heat transfer coefficients

(b) Local heat transfer coefficients

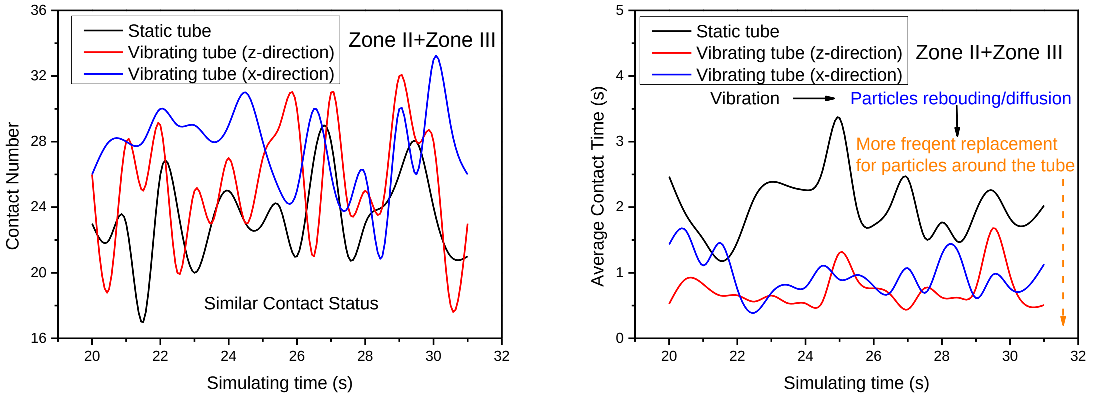
Figure 4: Comparison between static tube and vibrating tube on heat transfer coefficients



(a) Average contact time in Zone I

(b) Contact number in Zone IV

Figure 5: Comparison between static tube and vibrating tube on contact phenomenon



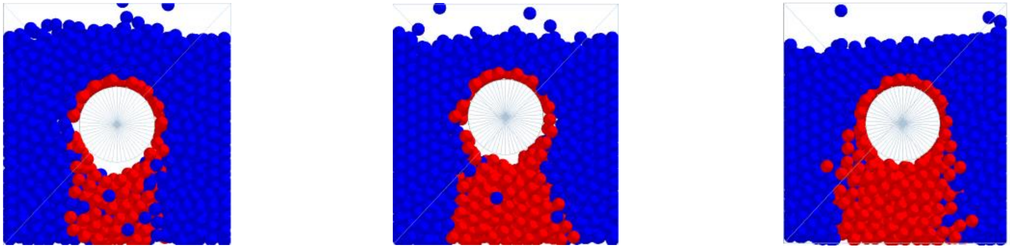
(6) Contact number in Zone II&III

(b) Average contact time in Zone II&III

Figure 6: Contact phenomenon on the side of tube

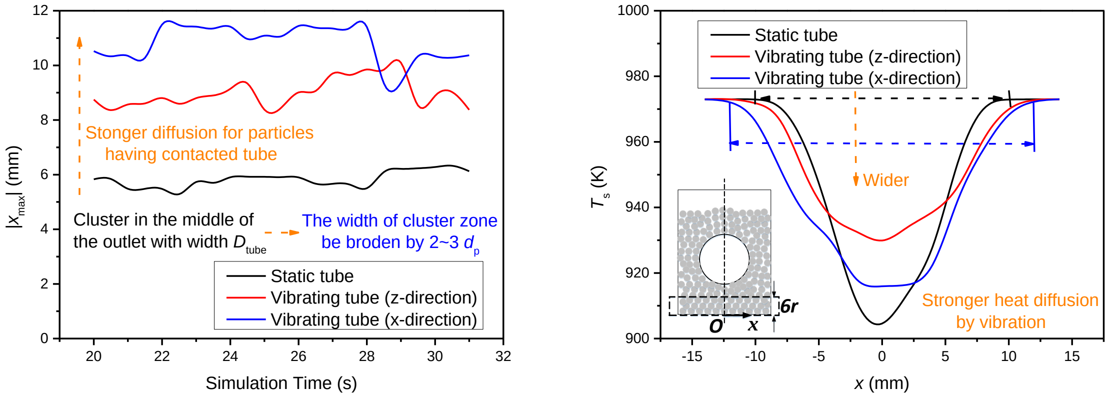
Besides, the contact on the side of tube is also presented in Figure 6. The contact numbers are in similar level for different occasions, which mean similar dense structure around tube. The primary difference is that contact time would decrease with vibration in the Zone II and Zone III. It results from that the vibration would rebound particles around the wall. It would make other particles occupy the place around the tube, which were away from the tube before. Hence, particles update is also improved and the contact time would decrease.

The process above could be seen as that particles contacting tube before would diffuse with vibration, as presented in Figure 7. The diffusion could reflect the disturbance of granular flow around the tube, which is alike to boundary layer breaking in turbulence. The phenomenon is beneficial to heat transfer, where particles in higher temperature contact the tube easily and penetration resistance would decrease. The max diffusion distance in x-coordinate varying with time is demonstrated in Figure 8a, which is used to evaluate the effect. It's found that, the additional diffusion caused by x-direction vibration is stronger than that of z-direction vibration. The additional mass diffusion would bring additional heat diffusion. The law could be derived from the outlet temperature distribution in Figure 8b. The curves demonstrate that tube vibration would broaden the area where pariticles temperature has changed. It means more particles are affected by the tube. Hence, heat transfer in Zone II and Zone III is also strengthened by tube vibration.



(a) Static tube *(b) Z-vibration tube* *(c) X-vibration tube*

Figure 7: Distribution of particles whose contact time larger than 0 (red particles, t = 31 seconds)



(a) Max diffusion distance *(b) Outlet temperature distribution*

Figure 8: Effect of vibration on particles diffusion

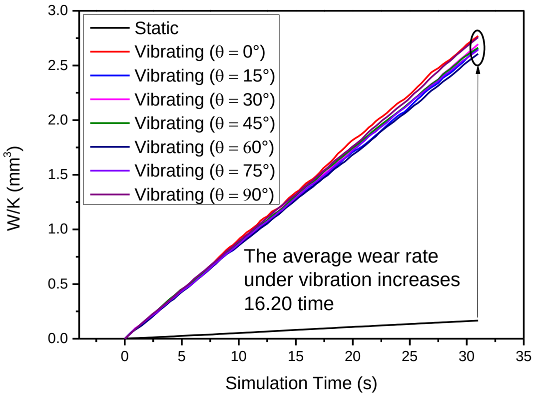


Figure 9: Effect of vibration on tube abrasion

However, it should be noted that there are abrasion coupling with vibration. It could be treated as the consumption of vibration technology. In the current work, Archard et al.,(1953) theory is implanted to evaluate the wear volume of tube. To isolate the effect of tube material on abrasion analysis, W/K in cases of static tube and vibration tube are illustrated in Figure 9. The value of W/K could reflect the status of tube wear. As shown in Eq(3), the wear losing volume (W) between the tube and particles, is a function of normal stress (p), material hardness (H) and the relative displacement (△s). In fact, normal stress (p) and material hardness (H) decide the contact deformation between particles and the tube. As for the parameter K, it’s a constant related to the tube material. Its magnitude is less than 10^{-3} (Archard et al.,1953).

$$W = Kp\Delta s / H \tag{3}$$

It’s found that vibrations in any directions would exacerbate the wear significantly. The trends of any vibrations are similar, and the average wear rate under the slight vibration would increase 16.20 time. The phenomenon results from the larger slip (△*s*) and extrusion (*p*) between tube and particles. Hence, even though tube vibration would enhance heat transfer, it also worsens the wear. It’s alike to that the fin inside tube increases heat transfer and pressure drop meanwhile. The industrial application of tube vibration technology relies on the development of wear-resistant technology, where *K* is less. Then, the actual wear loss could be controlled.

4. Conclusions

To enhance heat transfer between granular flow and the tube in moving bed heat exchanger (MBHE), the influence of sinusoidal tube vibration is investigated in details. Slight vibrations (D_A= 1.72 mm and f= 3 Hz.) in different directions are applied to the tube. Discrete element method (DEM) is developed for the simulation, which has been validated by means of a compromise proposal. The major findings are summarized as below: (1) Slight vibrations in any directions would cause denser contact and avoid more void around tube, which could enhance heat transfer. The x-direction vibration in the current work could increase heat transfer coefficients by 36.33 %, which achieves better improvement performance. (2) Tube vibration could rebound particles around the tube. Then, particles in higher temperature contact the tube easily and penetration resistance decreases. It brings additional mass diffusion couple with heat diffusion. The effect of x-direction vibration is more remarkable. (3) Even though tube vibration would enhance heat transfer, it also worsens the tube abrasion. The average wear rate under the slight vibration would increase 16.20 time compared with that of the static tube.

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